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POLICIES AND SUPPORT IN RELATION TO LCA

The search for an appropriate end-of-life formula for the purpose of the European Commission Environmental Footprint initiative

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Abstract
Purpose This paper explains in details the rationale behind the choice of the end-of-life allocation approach in the European Commission Product Environmental Footprint (PEF) and Organisational Environmental Footprint (OEF) methods. The end-of-life allocation formula in the PEF/OEF methods aims at enabling the assessment of all end-of-life scenarios possible, including recycling, reuse, incineration (with heat recovery) and disposal for both open- and closed-loop systems in a consistent and reproducible way. It presents how the formula builds on existing standards and how and why it deviates from them.
Methods Various end-of-life allocation approaches and formulas, mainly taken not only from/based on existing environmental impact assessment methods and/or standards but also one original linearly degressive approach, were analysed against a predetermined set of criteria, reflecting the overall aim of the PEF/OEF methods. This set of criteria is physical realism, distribution of burdens and benefits in a product cascade system and applicability. Besides the qualitative analysis, the various formulas were implemented for several products and for different scenarios regarding recycled content and recyclability to check the robustness of the outcomes, exemplary expressed for the Global Warming Potential impact category.
Results and discussion As reaching physical realism was impossible at both the product and overall product cascade system level by any of the end-of-life approaches analysed, one of both had to be prioritised. The paper explains in details why a product level approach was preferred in the context of the PEF/OEF methods. In consequence, allocation of the end-of-life processes which are related to more than one product in a product cascade system is needed and should be carefully considered as it has a major influence on the results and decision taking.
Conclusions A formula taking into account the number of recycling cycles of a material was identified as preferred to reach physical realism and to allocate burdens and benefits of repeatedly recycling of a material over the different products in a product cascade system. However, this approach was not selected for the PEF/OEF methods as data on the number of recycling cycles was insufficiently available (for the time being) for all products on the market and hence fails the criterion of "applicability". This explains why, instead, a formula based on the 50:50 approach—allocating shared end-of-life processes equally between the previous and subsequent product—was selected for the PEF/OEF methods.

Keywords Allocation · Closed-loop · End-of-life · Environmental footprint · Environmental life cycle assessment · Open-loop · Recycling

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1 Introduction

1.1 The need for a consistent and comprehensive life-cycle-based environmental assessment method

Life cycle assessment (LCA) is a broadly accepted method to assess pressures and burdens of products associated with emissions and resources consumed in their supply chains, use and end-of-life. International standards, i.e. ISO 14040:2006 and ISO 14044:2006, exist on how to carry out an LCA (ISO 2006a, b). As LCA can be used for several purposes, the ISO standards needed to be flexible and therefore only comprise general guidelines (Galatola and Pant 2014). In consequence, LCA studies can be incomparable or even sometimes lead to contradictory results due to different assumptions regarding amongst other system boundaries, environmental impact categories and/or models and data specifications (Villanueva and Wenzel 2007). As a response to this, several more detailed and prescriptive methods have been developed based on the ISO standards for different applications, sectors and product groups. Examples of such methods are the Greenhouse Gas Protocol (WRI and WBCSD 2011), the French BPX 30-323-0 regarding environmental communication of products (AFNOR 2011) and the UK PAS 2050 for the assessment of the life-cycle greenhouse gas emissions of goods and services (BSI 2011). These all relate to a broad scope of products, while also LCA-based standards exist for specific groups of products such as, for example, the CEN standards EN 15804+A1 (CEN 2013) and EN 15978 (CEN 2011) for construction products and buildings, respectively. This proliferation of environmental assessment methods potentially leads to inconsistencies and unnecessary work for companies. Also, consumers are confused by incomparable and diverse environmental information: according to a recent Eurobarometer (http://ec.europa.eu/public_opinion/flash/fl_367_en.pdf, accessed 17 July 2014), 48 % of European consumers are confused by the stream of environmental information they receive. This also affects their readiness to make green purchases.

In the context of the recent Building the Single Market for Green Products Package (EC 2013a; http://ec.europa.eu/environment/eussd/smgp/index.htm), the European Commission (EC) proposes a set of actions to overcome these problems:

- It establishes two methods to measure environmental performance throughout the life cycle, the Product Environmental Footprint (PEF) and the Organisation Environmental Footprint (OEF);
- It recommends the use of these methods to Member States, companies, private organisations and the financial community through a Commission Recommendation (EC 2013b);
- It announces a 3-year testing period to develop product- and sector-specific rules through a multi-stakeholder process;
- It provides principles for communicating environmental performance, such as transparency, reliability, completeness, comparability and clarity.

The EC highlighted already more than a decade ago the importance of LCA in its Integrated Product Policy Communication (EC 2003) and outlined a strategy to provide common support to the Union. This included the development of the European Platform on LCA (http://eplca.jrc.ec.europa.eu/), the International Reference Life Cycle Data System (ILCD), and the European Reference Life Cycle Database (ELCD) (EC-JRC-IES 2010). Building on these, and on national/international initiatives, with the EC Environmental Footprint (EF) method (EC 2013b), the EC developed a comprehensive and consistent European life-cycle-based method.

1.2 The EC environmental footprint methods

The technical/scientific development of the EC environmental footprint (EF) methods was led by the Institute for Environment and Sustainability (IES) of the Joint Research Centre (JRC), a Directorate General of the EC, in close cooperation with the EC Directorate General Environment (DG ENV). The EC Environmental Footprint is a multi-criteria measure of the environmental performance of products (i.e. goods and/or services) and organisations from a life cycle perspective. EC EF studies are performed for the overarching purpose of seeking to reduce the pressures of products and organisations in the context of resource efficiency and the environment, taking into account supply chain activities (from extraction of raw materials, through production and use, to final waste management).

With the EF method, the EC is responding to the Council of the European Union, which in its conclusion on the "Sustainable materials management and sustainable production and consumption" (Council 2010), invited the Commission to "develop a common methodology on the quantitative assessment of environmental impacts of products, throughout their life cycle, in order to support the assessment and labelling of products".

It is a supporting method to the EC's objective to "establish a common methodological approach to enable Member States and the private sector to assess, display and benchmark the environmental performance of products, services and companies based on a comprehensive assessment of environmental impacts over the life cycle ('environmental footprint')" (EC 2011). The need for such a comprehensive and consistent LCA method in a policy context was also acknowledged by researchers (Wardenaar et al. 2012). The EC EF methods hence strives for providing reproducible and comparable assessments of products and organisations by ensuring physically realistic modelling and being technically detailed and prescriptive. In the discussion paper "Product environmental footprint—breakthrough or breakdown for policy implementation of life cycle assessment", Finkbeiner (2014) questions several methodological issues of the EC EF methods. Galatola and Pant (2014) provided arguments for the methodological choices made in their reply to Finkbeiner's discussion paper. The general aim and methodological decisions of the EC EF methods are not further discussed here. This paper focuses on the end-of-life (EoL) approach in the EC EF methods by providing insights in the analysis of existing EoL approaches which were considered during the development of the EC EF methods.

1.3 Goal and scope of the end-of-life assessment in the EC EF methods

The goal of the EoL part of the assessment is in line with the overall goal of the EC EF methods, i.e. allowing for assessing products in a consistent and comprehensive way in order to provide reproducible and comparable assessments of products, by ensuring physically realistic modelling and being technically detailed and prescriptive. In order to allow for this consistency, while remaining feasible also for complex products, a single prescriptive EoL calculation method (i.e. formula) was preferred above a set of several approaches for different products. Such a single-formula approach that was most promising for the PEF/OEF EoL formula can also be seen as a valuable option in the context of standardisation and labelling and is, more generally, important when striving for harmonisation and consistency in LCA, in the overall aim of comparability. An important objective of the EOL approach in the EC EF methods is hence supporting comparability.

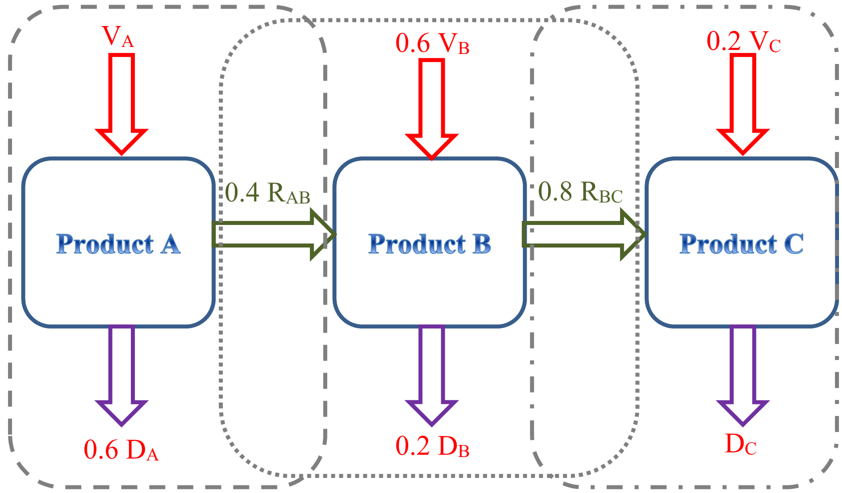
The scope of the EoL assessment of the EC EF methods includes all possible EoL strategies applicable to products such as reuse, recycling, incineration—with or without energy recovery—and final disposal via landfill. For the recycling strategy, these processes should be assessed consistently for both open-loop (i.e. a material from one product system is recycled into another, different product system) and closed-loop systems (i.e. a material from one product system is recycled back into the same product system). For open-loop systems, it is moreover important to consider down-cycling, i.e. loss of quality, when appropriate (Kim et al. 1997; Werner and Richter 2000). As the EC EF methods considers the whole life cycle of products, the assessment is not limited to recycling or reuse at the EoL stage but includes also the recycled content of products (e.g. the recycled content that is used in the production of products B and C in Fig. 1). Although the aim is to cover both recycled content on the input side and recyclability at end of life, double counting of burdens and/or benefits should be avoided as this would clearly conflict with the aim of physically realistic modelling.

In summary, the objectives of the EoL approach in the EC PEF method are the following: supporting comparability at product level (i.e. to allow for labelling products), being comprehensive by including both recycled content and recyclability, enhancing acceptance, being applicable for any product on the market and being physically correct. These objectives and their consequences are further explained in the subsequent sections.

1.4 System boundaries and EoL allocation

In terms of the environmental footprint of products, there is an issue of how to define the system boundaries when considering the EoL. Should the overall system be assessed (e.g. products A and B and C in Fig. 1) or should the assessment be limited to a single product (indicated by a dashed/dotted line in Fig. 1)? If this second (product) approach is chosen, how should the product boundaries be defined? Is recycling of product A still to be included in the system boundary of product A or does it belong to product B in terms of recycled content? Or should it be included in the model for both separate products (leading to double counting at the overall cascade system level)? Or should the recycling process of product A be partially assigned to product A and partially to product B? And should this be done on an equal basis (50%) or is one product more "responsible" for the recycling process than the other? This allocation could for example be based on a causal, physical relationship or based on the economic value of both products. Although some people find economic allocation too arbitrary, other prefer it because they see it as the only feasible procedure for allocation or because they are convinced that market prices reflect the functionality of a material quality. They moreover argue that the system boundary and related allocation will anyway be arbitrary (Ekvall 2000; Werner and Richter 2000; Borg et al. 2001). The discussion then extends also in relation to recycled content. Is only product A responsible for all the virgin production related to product A, while this facilitates three products in the system (A, B and C), or should part of this burden be shared/allocated with also products B (and C)? If so, on which basis should the impact be distributed? On the basis of economic value as proposed by, e.g. Borg et al. (2001) or on the basis of quality difference as proposed by, e.g. Kim et al. (1997) or on another basis as, for example done in the 50/50 approach of the BPX 30-323-0 method (AFNOR 2011)? Similar questions can be posed regarding the burdens due to the disposal of products B and C. The challenging issue of EoL allocation is discussed by many scientists (e.g. Kim et al. 1997; Byström and Lönnstedt 2000; Vogtländer et al., 2001; Pears and Grant 2005; Nicholson et al., 2009; Frischknecht 2010). Within the discussion on EoL assessment, two main approaches can be distinguished:

Fig. 1 Product cascade system comprising different EoL scenarios: *product A* recyclability of 40%, *product B* recycled content of 40% and recyclability of 80%, *product C* recycled content of 80%. (V_i virgin production for product *i*, D_i disposal of product *i*, R_{ij} recycling of product *i* into product *j*)



an overall system approach and a product approach. The solution of *system boundary expansion* by including all products of the overall product cascade system is scientifically unambiguous (Klöpffer 1996). This approach is however questionable for the purpose of labelling of products because it does not differentiate between products A, B and C, for example in Fig. 1, while these are clearly not identical. A product approach hence seems more appropriate for the purpose of the EC EF methods or for any other method aiming at the labelling of products.

1.5 Objectives and scope of the paper

This paper focuses on defining system boundaries and related allocation schemes in EoL modelling inherent to a product approach, as is the case of the EC EF methods. More specifically, the focus is on the search for the most appropriate choices in the EoL modelling within the overall aim of labelling the environmental impact of products from a life cycle thinking perspective, in a comprehensive way. The paper does not intend to provide an exhaustive overview of and/or in-depth discussion on potential EoL approaches found in literature. Instead, it focuses on a selected number of EoL approaches mainly taken from existing standards or widely used methods as enhancing acceptability was one of the objectives of the EC EF methods. It is explained how the EoL formula of the EC EF methods was built on existing standards, and for which aspects it deviates from them, and for what reasons considering the specific objectives of the EC EF methods. The goal was furthermore to analyse the robustness of the formulas by testing the most promising ones for several products and for one impact category, global warming potential.

The paper is limited to the discussion of allocation related to reuse, recycling and disposal. It does not focus on incineration with or without energy recovery. The latter can however be addressed analogously and is included in the EoL formula of the EC EF methods. Although the primary aim of this paper is to provide insights regarding the EoL formula in the EC EF methods, it may also provide insights for decision taking regarding EoL approaches in other LCA contexts, especially if the challenge is to address recycled content on the input side at the same time as recyclability at the end of life of the product under investigation.

In the subsequent section, the approach followed for the selection/development of the EoL calculation method in the EC EF methods is described. In Sect. 3, the analytical results are presented and discussed. In Sect. 4, the conclusions are summarised.

2 Methods

2.1 Selection of potential EoL approaches and translation into EoL formulas

As the EC EF methods aim at providing a common base for measuring and communicating the environmental performance of products and organisations, an agreed basis as a starting point was important. This is also the case for the EoL approach. To enhance acceptability, existing EoL approaches in standards and guidelines were taken as a starting point. This work hence builds on previous efforts by analysing five existing approaches (i.e. occurring in one or several standards) and one additional new approach (i.e. not occurring in any standard as far as known by the authors) for EoL modelling. The EoL approaches followed in the following standards, methods and guidelines were considered in our analysis: PAS2050 (BSI 2011), BP X 30-323-0 (AFNOR 2011) and ISO/DIS 14067 (ISO 2012). These approaches were translated in 11 formulas which were analysed in detail to check their appropriateness for the EC EF methods. The different approaches and their translation into formulas are described in the subsequent subsection and an overview of the 11 formulas is provided in Table 1. The approaches and corresponding

Table 1 Overview of the 11 analysed EoL formulas

Formula	Name	Formula
1a	0:100, no credit	$EF = E_V + R_2 \times E_{recycling,EoL} + (1 - R_2) \times E_D$
1b	0:100, credit for avoided virgin production[a]	$EF = E_V + R_2 \times \left(E_{recycling,EoL} - E^*_V \times \frac{Q_S}{Q_P}\right) + (1 - R_2) \times E_D$
2	100:0, no credit	$EF = (1 - R_1) \times E_V + R_1 \times E_{recycled} + (1 - R_2) \times E_D$
3a	100:100, no credit	$EF = (1 - R_1) \times E_V + R_1 \times E_{recycled} + R_2 \times E_{recycling,EoL} + (1 - R_2) \times E_D$
3b	100:100, credit for avoided virgin production[a]	$EF = (1 - R_1) \times E_V + R_1 \times E_{recycled} + R_2 \times \left(E_{recycling,EoL} - E^*_V \times \frac{Q_S}{Q_P}\right) + (1 - R_2) \times E_D$
3c	100:100, credit for avoided production of mix at input side[b]	$EF = (1 - R_1) \times E_V + R_1 \times E_{recycled} + R_2 \times \left(E_{recycling,EoL} - E^*_V \times \frac{Q_S}{Q_P}\right) + (1 - R_2) \times E_D$
3d	100:100: crediting for avoided virgin production a ratio of $\min(R_2,\lvert R_2 - R_1\rvert)$[a]	$EF = (1 - R_1) \times E_V + R_1 \times E_{recycled} + R_2 \times E_{recycling,EoL} - \min(\mathrm{abs}(R_2 - R_1), R_2) \times E^*_V \times \frac{Q_S}{Q_P} + (1 - R_2) \times E_D$
4a	50:50, no credit	$EF = (1 - R_1) \times E_V + \frac{R_1}{2} \times E_{recycled} + \frac{R_2}{2} \times E_{recycling,EoL} + (1 - R_2) \times E_D$
4b	50:50, credit for avoided virgin production a ratio of $R_2/2$[a]	$EF = (1 - R_1) \times E_V + \frac{R_1}{2} \times E_{recycled} + \frac{R_2}{2} \times \left(E_{recycling,EoL} - E^*_V \times \frac{Q_S}{Q_P}\right) + (1 - R_2) \times E_D$
5	BPX 50/50_adapted[a, c]	$EF = \left(1 - \frac{R_1}{2}\right) \times E_V + \frac{R_1}{2} \times E_{recycled} + \frac{R_2}{2} \times \left(E_{recycling,EoL} - E^*_V \times \frac{Q_S}{Q_P}\right) + \left(1 - \frac{R_1}{2} - \frac{R_2}{2}\right) \times E_D$
6	Degressive, linearly	For all except $R_1 = R_2 = 1$: $EF = (1 - R_1) \times \left(\frac{(2 \times n - 1)}{n^2} \times E_V + \frac{E_D}{n^2}\right) + (1 - R_2) \times \left(\frac{E_V}{n^2} + \frac{(2 \times n - 1)}{n^2} \times E_D\right) + \frac{R_1}{2} \times E_{recycled} + \frac{R_2}{2} \times E_{recycling,EoL}$ For $R_1 = R_2 = 1$: $EF = \left(\frac{E_V}{n} + \frac{E_D}{n}\right) + 0.5 \times E_{recycled} + 0.5 \times E_{recycling,EoL}$

[a] With $E_V = E_V$ (closed-loop assumed)

[b] With $E_V = (1 - R_1) \times E_V + R_1 \times E_{recycled}$ (closed-loop assumed)

[c] The BPX 50/50 approach was slightly adapted to enable differentiating between $E_{recycled}$ and $E_{recycling,\ EoL}$ and to enable including changes in inherent material properties, i.e. by including Q_S/Q_P

formulas differ in (1) allocation approach regarding the burdens of EoL processes and in (2) allocation of the so-called credits (avoided production and disposal) due to recycling (and reuse).

2.1.1 Approaches considered for the allocation of the environmental burdens of recycling

For the allocation of the EoL processes, five *existing approaches* were analysed and summarised below. In a later step (see further), the approaches have been translated into EoL formulas. For transparency reasons, reference to these formulas is already mentioned for each of the approaches. For some approaches, several formulas are mentioned which relates to different allocation approaches related to avoided/reduced flows (i.e. avoided burdens) upstream. The latter is further discussed in Sect. 2.1.2. The following five existing approaches were analysed:

- Full allocation of the recycling impact to the product producing a recycled material and no burdens allocated to downstream products using input recycled materials (sometimes referred to as 0:100 approach or recyclability substitution approach or EoL recycling approach) (formula 1a + 1b in Table 1);
- Full allocation of the recycling impact to the product using a recycled material, with no burdens from recycling operations allocated to the upstream product (sometimes referred to as 100:0 approach or recycled content approach or cutoff approach) (formula 2 in Table 1);
- Full allocation of the recycling impact to both the product producing a recycled material and also to the product using a recycled material (sometimes referred to as 100:100 approach) (formula 3a–d in Table 1);
- Fifty-per cent allocation of the recycling impact to the product producing a recycled material and 50% to the product using the recycled material (sometimes referred to as 50:50 approach) (formula 4a + 4b in Table 1);
- BPX 50/50-based approach. This approach does not only distribute the impacts due to recycling in a 50:50 manner but also the virgin and disposal impact over the different products in the overall product cascade system (formula 5 in Table 1). It should be noted that we slightly adapted the original BPX 50/50 formula to enable differentiating

between recycled content (E_{recycled}) and recyclability ($E_{\text{recycling,EoL}}$) and to enable considering changes in inherent material properties (as was identified to be necessary for the purpose of the EC EF methods).

Four of these five approaches have been selected from existing standards and widely used methods in order to enhance acceptability. The 0:100 approach is, for example used by the PAS 2050 method (BSI 2011, p. 31) in its closed-loop approximation “if the recycled material maintains the same inherent properties as the virgin material” and referred as “closed-loop approximation”. The 100:0 approach is, for example proposed by Buhé et al. (1997) and used by the PAS 2050 method (BSI 2011, p. 31) “if the recycled material does not maintain the same inherent properties as the virgin material input” and by the BP X 30-323-0 method for closed-loop systems (AFNOR 2011, p. 19). It is moreover in line with the approach of the EN 15804 for construction products. The BP X 50/50 approach is used in the latter method for “open-loop system recycling if the market shows no visible disequilibrium” (AFNOR 2011, p. 19). Equally dividing impacts related to recycling was moreover recommended by several organisations and researchers such as the suggestion by SETAC for recycling systems to “equally divide impacts added to the system because of recycling” (Fava et al. 1991, p. 80), the recommendation of the 50/50% allocation for simplified LCA and for loads caused by waste management and recycling processes by the European Environment Agency (Jensen et al. 1997) and the recommendation by the Nordic Guidelines for LCA to use the 50/50 approach for key issue identification to ensure that these are not lost in cascade coupled recycling systems (Lindfors et al. 1995). The translation of these approaches in formulas in existing methods is however not necessarily identical to the translation made in this paper for the purpose of the EC EF methods (Table 1). We refer to another paper for a detailed description and comparative analysis of the EoL formula as implemented in the EC EF methods and several other widely used methods. (Allacker et al. 2014). The third approach, the 100:100 approach, does not occur in any standard but is included in the analysis as the aim of the EoL approach in the EC EF methods is to include both recycled content and recyclability and the 100:100 approach is one of the options fulfilling this aim.

Additionally, a *new approach* (*i.e. not occurring in any standard as far as known by the authors*) was proposed and translated in an EoL formula (formula 6 in Table 1). This new approach, referred to as “linearly degressive approach” uses the 50:50 approach for the allocation of the recycling impact. The impact of the virgin production is however allocated in a linearly degressive way to all products in the product cascade system, allocating the highest share of impact to the first product. The impact due to final disposal is also allocated in a linearly degressive way to all products in the overall system, but allocating the highest share of impact to the last product. This is schematically presented in Fig. 2 for a product cascade system consisting of three products (n = 3). Although this concept of a linearly degressive approach for the EoL allocation is not yet integrated in existing standards, it has been discussed by previous researchers.

2.1.2 Approaches considered for the allocation of the credits due to recycling

Two important consequences (and drivers) of recycling is the reduction in the use of virgin resources and the reduction in waste disposal. The reduced waste disposal is typically a direct consequence for the product being recycled, while the reduced use of virgin resources is typically a physical consequence for the product using recycled content. These physical consequences—as well as the recycling process burden—need to be taken into account in the assessment of one or several products in the overall cascade system. It is hence important to investigate different options in allocating these benefits over the different products of the cascade system in order to make a profound choice for the purpose of the EC EF methods. For each of the six approaches described in Sect. 2.2.1, several options are possible for the allocation of credits due to recycling (i.e. avoided use of virgin production and avoided impacts of disposal), at EoL and/or when using recycled content. Following options were analysed:

- For the 0:100 approach:

  – No credit (formula 1a);
  – Credit for the avoided virgin production a ratio of the R_2. It is thus assumed that the recycled material from the product life cycle analysed replaces virgin material in the expanded system (formula 1b);

- For the 100:0 approach:

  – No credit (formula 2);

- For the 100:100 approach:

  – No credit (formula 3a);
  – Credit for the avoided virgin production a ratio of the R_2. It is thus assumed that the recycled material from the product life cycle analysed replaces virgin material in the expanded system (formula 3b);
  – Credit for the avoided virgin production but to a smaller extent: i.e. a ratio of the minimum of the R_2 or difference between R_2 and recycled content (R_1; i.e. $\min(R_2,|R_2-R_1|)$). This would, for example equal 40% (instead of 80%) for product B in Fig. 1 (formula 3c);

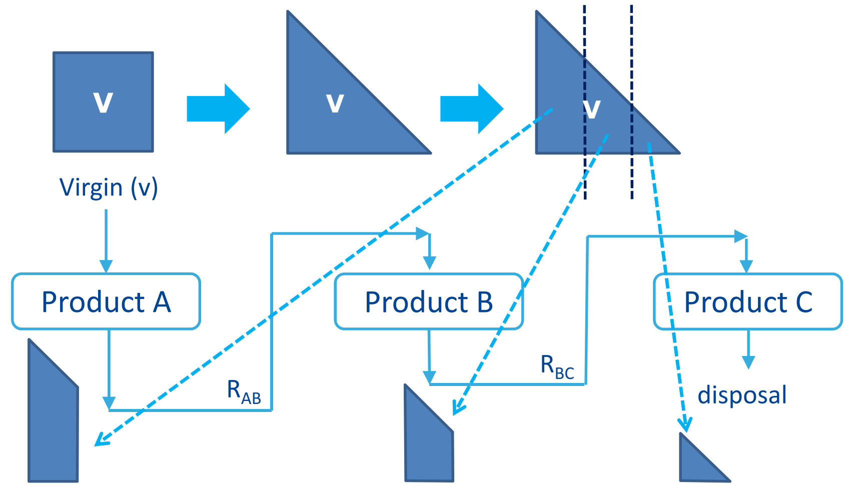


Fig. 2 Scheme representing the linearly degressive approach for EoL allocation for the example of a product cascade system consisting of three products ($n = 3$)

– Credit for the avoided production of the production mix (virgin + recycled content) at input side a ratio of the R_2. In this case, it is assumed that the recycled material from the product life cycle analysed replaces the same input mix in the expanded system (formula 3d);

- For the 50:50 approach:

– No credit (formula 4a);
– Credit for the avoided virgin production a ratio of $R_2/2$. It is thus assumed that the recycled material from the product life cycle analysed replaces virgin material in the expanded system (formula 4b);

- The BPX approach credits for avoided virgin production a ratio of $R_2/2$. It furthermore differs from the 50:50 approach with credits (as analysed in this paper) in distributing also both the virgin production and disposal impacts over the different products in the overall system.

For each of the options which credit avoided production, a quality correction ratio (Q_S/Q_P) is considered in our assessment. This ratio reflects any difference in quality between the secondary material and the primary material ("downcycling"). This quality correction ratio forms part of the allocation approach as it can be calculated on different bases such as a relevant underlying physical relationship or economic value. For the EC EF methods, it was decided to use the allocation hierarchy of the ISO 14044 standard, giving preference to the first over the latter approach (ISO 2006b) because one of the aims of the EC EF methods is to ensure physically realistic modelling. Vogtländer et al. (2001, p. 3) further argues that several criteria should be met for allowing economic allocation (i.e. relatively stable prices in a transparent, free and open market; and a linear relationship between market value and mass, volume and/or time). Boguski et al. (1994) propose to use a mass-based allocation and not only for the credits due to avoided production but also for the allocation of the recycling process and disposal. The EC EF methods do not include prescriptive rules on how to define Qs/Qp as these may have to be defined differently for different product groups. Prescriptive rules on the calculation of this correction ratio needs to be defined in the EF Category Rules to ensure harmonisation within each product group. An in-depth discussion on this parameter hence falls outside the scope of this paper.

Definition of Terms Used in Formulas

- EF: emissions and resources consumed (per unit of analysis) arising from the production and the EoL stages of the product life cycle.[1]
- E_V = emissions and resources consumed (per unit of analysis) arising from the acquisition and pre-processing of virgin material.
- E^*_V = emissions and resources consumed (per unit of analysis) arising from the acquisition and pre-processing of virgin material assumed to be substituted by recyclable materials.
- $E_{recycled}$ = emissions and resources consumed (per unit of analysis) arising from the production process of the recycled material, including collection, sorting and transportation processes.
- $E_{recyclingEoL}$ = emissions and resources consumed (per unit of analysis) arising from the recycling process at the EoL, including collection, sorting, transportation and recycled material production processes.
- E_D = emissions and resources consumed (per unit of analysis) arising from disposal of waste material (e.g. landfilling, incineration and pyrolysis).

[1] For this paper, only the production and EoL stages are included as other life cycle stages (e.g. use stage) relate to one product and therefore do not require allocation between the products of the cascade system.

- R_1 (dimensionless) = “recycled content of material”, is the proportion of material in the input to the production that has been recycled in a previous system ($0 = < R_1 < = 1$).
- R_2 (dimensionless) = “recycling fraction of material”, is the proportion of the material in the product that will be recycled in a subsequent system, i.e. the rate between recycled output and virgin material input. R_2 shall therefore take into account the inefficiencies in the collection and recycling processes ($0 = < R_2 = < 1$).
- Q_S = quality of the secondary material, i.e. the quality of the recycled material.
- Q_P = quality of the primary material, i.e. the quality of the virgin material.
- n = the number of recycling cycles, i.e. the number of subsequent products produced out of virgin material.

2.2 Description of the analysis

As described in the previous sections, a number of potential EoL approaches has been selected which fulfil the objectives of supporting comparability at product level (i.e. allowing for an assessment at product level and not at overall system level) and enhancing acceptance (i.e. based on their occurrence in current standards and/or widely used methods). These have been translated in formulas which allow for straightforward assessment, which is found important in terms of the first objective of comparability (i.e. product labelling). In a next phase, these 11 EoL formulas have been analyse, following a two-step procedure (Fig. 3).

During these steps, the different approaches were analysed in terms of three criteria reflecting the remaining objectives of the EC EF methods and identified based on literature review. The three criteria are the following:

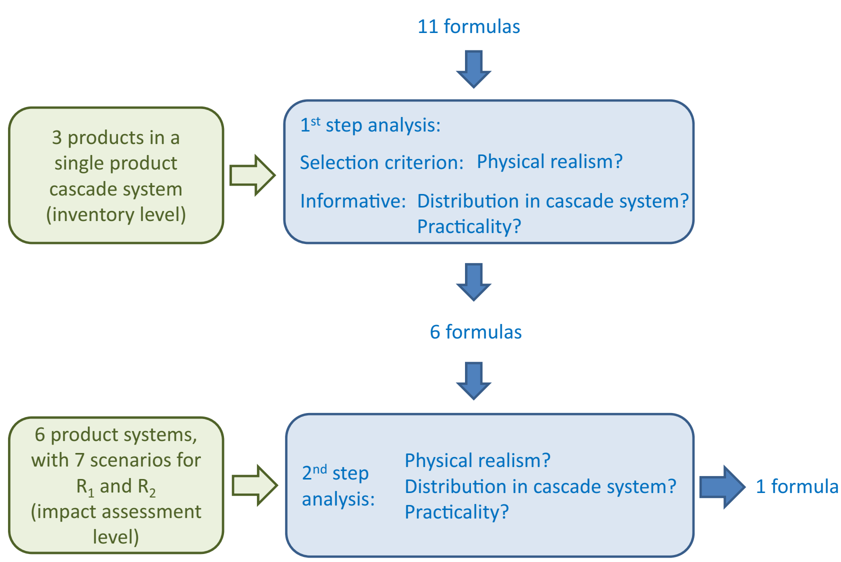
“Physical realism”: physical correctness of the outcomes. This criterion evaluates if the modelling correctly represents the flows and related mass balances. The analysis is made at product level and overall system level. This criterion relates to the objective of being physically correct;

- “Distribution in a cascade system”: this refers to a “fair” distribution of burdens and benefits over the different products in the cascade system. The term “fair” is debatable and depends on the perspective of the individual. The assessment of this criterion in the paper reflects how the different formulas fit different viewpoints on “fairness”. This criterion is hence analysed from different viewpoints and is not an excluding criterion, only an informative one. This criterion relates to the objectives of being comprehensive and being physically correct;
- “Practicality”: applicability to the majority of the products on the market. This criterion evaluates the feasibility of the chosen allocation approach and relates to the objective of being applicable for any product on the market.

These three criteria were also identified by other researchers as necessary to ensure acceptability of an EoL approach. More specifically, our criteria are in line with the criteria of fair distribution and feasibility of Klöpffer (1996); the three criteria proposed by Ekvall and Tillman (1997), i.e. effect-oriented causality (relates to distribution in a cascade system), acceptability (relates to our criterion of physical realism) and applicability (relates to our criterion of practicality); and the criterion “fairness or equity” of Frischknecht (2000) which relates to our criterion of distribution in a cascade system.

Our first criterion physical realism is seen as essential for the purpose of the EC EF methods and was therefore used as a selection criterion in the first step of analysis.

Fig. 3 Two-step procedure followed for the analysis of the EoL formulas



Within this criterion, it was investigated if the input and output flows are correctly modelled (i.e. correct physical flows) at both the product and overall product cascade system level. It was checked if the mass balance is maintained in the product system, but also if the processes that take place are indeed accounted for. For example, if the modelling of a product which completely consists of recycled content (no virgin content) and which is disposed at the end, would result in the impact of virgin production and disposal, the mass balance is correct, but the processes that really take place are not correctly assessed.

The second criterion distribution in a cascade system is included because a product approach is chosen and thus subjective allocation is necessary. The analysis identifies which formula(s) is/are preferred for several viewpoints (value choices) regarding “fair” distributions of impacts along the different products of the overall system. “Fair” is difficult to define and is likely to depend on the perspective of the individual. Ekvall and Tillman (1997) present eight different perspectives and allocation procedures that can be considered fair from each perspective. This criterion is clearly value based. It discusses which product is found responsible for which processes due to the chosen allocation approach and hence how each formula fits a certain perspective (i.e. can be considered “fair” to a certain perspective). This criterion is assessed for all formulas considered but is not considered for eliminating any of the proposed formulas. It is an informative criterion, only included to give transparent information regarding the formulas analysed.

The third criterion practicality is included because the EC EF methods, including the EoL formula, need to be applicable for all products on the market and need to be reasonably straightforward to apply. This criterion checks if the proposed approach does not require the input of unknown parameters (for some or several products on the market). Four levels of practicality were distinguished: “very high (+++)”, “high (++)”, “normal (+)” and “low level (−)”. The highest level (+++) was assigned to those formulas which do not require to know the recycling process at EoL ($E_{\text{recycling, EoL}}$). It is assumed that this is more difficult to know (higher level of uncertainty) than the recycled input process (which has already occurred). The second level (++) of practicality was assigned to those formulas which do require to know the recycling process at EoL but do not require to estimate the avoided virgin production due to recycling at EoL. This was the case for all formulas which do not assign credits due to avoided virgin production. The third level (+) of practicality was assigned to formulas which do require to estimate this avoided virgin production. A low level of practicality (−) is assigned to the formula requiring to know the number of times a product/material is being recycled. Similar to the second criterion, this criterion is analysed for all formulas considered, but it is not used to exclude any of the formulas.

2.2.1 First analytical step

During the first step in the analysis, the three criteria were analysed by evaluating the outcome of three products in a single product cascade system, i.e. product (A) consisting of 100% virgin material, being 100% recycled at its EoL, product (B) consisting of 100% recycled material, being 100% recycled at its EoL and product (C) consisting of 100% recycled material being 100% disposed at its EoL. The outcome at the overall product cascade system level of these three products was moreover also checked against the first criterion. The analysis in this first step was limited to the inventory level; it does not include an impact assessment. If any other important issue beside these three criteria was identified, this has been reported as additional comment.

Based on this first step, six formulas were selected for a more in-depth robustness analysis (i.e. second analytical step).

2.2.2 Second analytical step

In the *second analytical step*, the six selected EoL formulas were applied to six different product systems (Table 2). The products analysed consist of three real cases (i.e. aluminium, paper and PVC) and three extreme (fictive) cases. The three extreme cases assume (i.e. EX 1) a higher impact due to recycling than to virgin production (i.e. EX 2), a lower (50%) impact due to recycling than to virgin production and (i.e. EX 3) a high impact due to disposal (higher than virgin production). In the EC EF methods, the EoL formula refers to the life cycle inventory (LCI) data. However, for this second analytical step, the EoL formulas are applied at the environmental impact level, more specifically, the analysis is made for climate change, expressed in kilogramme CO_2 equivalents. This choice is made in order to allow for a concise and understandable discussion. Although in EC EF studies the EoL formula is applied at LCI level, the principles are identical.

For the analysis of the real cases, specific data are used, while for the fictive cases, assumptions are made. All should be seen as illustrative and were not included to analyse them as such but served only to understand the outcomes of the six selected formulas. The analysis enables to investigate the importance of the different processes (i.e. virgin production, recycling process, disposal) and the different ratios (i.e. recycled content and recyclability) in the overall assessment. For each of these product systems, seven scenarios regarding recycled content (R_1) and recyclability (R_2) were analysed (Table 3).

Table 2 Product systems

	E_V	$E_{recycled} = E_{recycling, EoL}$	E_D	Q_S/Q_P	Unit of impact	Source
Aluminium	9.7	0.5	0	1	kg CO_2-eq./kg	EAA 2008
Paper	0.6	0.3	0.5	0.5	kg CO_2-eq./kg	SCA 2014[a]
PVC	2.01	0.32	0.0659	1	kg CO_2-eq./kg	Ecoinvent v2.2[b]
EX 1, $E_R > E_V$	9.7	15	0	1	kg CO_2-eq./kg	–
EX 2, $E_R = 0.5E_V$	9.7	5	0	1	kg CO_2-eq./kg	–
EX 3, $E_D > E_V$	9.7	0.5	15	1	kg CO_2-eq./kg	–

[a] The data for paper are not site specific but should be seen as data in the correct order of magnitude

[b] Swiss Centre for Life Cycle Inventories (2013). The CO_2-eq./kg are calculated with the "CML2001-Global Warming 100a" method as available in the Simapro Software (Pré Consultants 2012)

3 Results

3.1 Results of the first step of the analysis (inventory level)

The results of the first step of the analysis are summarised in Table 4. The first part of the table (columns 3–6) summarises the analysis of physical realism at both the product and overall systems level. A red colour indicates non-realistic physical modelling, while a green colour indicates realistic physical modelling. The second part (columns 7–9) provides information on how the burdens of virgin production, recycling and disposal are distributed over the three products in the product cascade system. It does not include any judgement but is only informative. The third part (column 10) indicates the level of practicality. Additional comments are included in column 11. The analysis presented in Table 4 of the 11 formulas revealed that:

- None of the formulas enables physically realistic results at both the product and the overall system level. It confirms the fact that priority needs to be given to one of both;
- Only one formula, i.e. the 100:100 approach without credits, enables a correct physical result at the product level for the three products considered;

Table 3 Scenarios for recycled content rate (R_1) and recyclability rate (R_2)

Recycled content (R_1)	Recyclability (R_2)
0%	0%
100%	100%
0%	100%
100%	0%
80%	30%
30%	80%
30%	95%

- Five formulas provide a realistic modelling at the overall system level:

– Crediting for avoided virgin production, 0:100;
– Without crediting, 100:0;
– Without crediting, 50:50;
– BPX 50/50_adapted;
– Degressive linearly

- The distribution in a cascade system criterion is a more debatable one, but overall in any product-oriented approach, the following questions are to be considered:

– Should the impact of the virgin production be entirely allocated to the first product in the chain? If so, approaches "50:50, no credit", "100:100, no credit" and "100:0, no credit" are in line with this idea.
– Or should the products which use recycled material out of this virgin production also be allocated part of the impacts as this virgin production was needed to produce the recycled material? If so, approaches "BPX 50/50_adapted" and "degressive linearly" are in line with this idea but consider different allocation rules;
– Should the impact of the recycling process be entirely allocated to the product producing the recycled material? This is the approach followed by the approaches "100:0". Or should it be allocated to the product using the recycled material, as is assumed by "0:100" approaches? Or to both, as for the "100:100" approach? Or should it be (evenly) distributed between the two products, as for the "50:50", BPX 50/50_adapted and degressive linearly approaches?;
– Should the impact of disposal entirely be allocated to the disposed product? The majority of the methods are in line with this idea except for BPX 50/50_adapted and

Table 4 Evaluation of the EoL formulas according to the criteria physical realism, distribution in a cascade system and practicality

[1]Approach	Credits	Physical realism				Distribution in a cascade system			Practicality	Other comments
		Product A	Product B	Product C	Products A + B + C					
		$R_1 = 0, R_2 = 1$	$R_1 = R_2 = 1$	$R_1 = 1, R_2 = 0$	Overall system	Virgin production	Recycling	Disposal		
0:100	No	$V + R^{a}$	$V + R^{b}$	$V + D^{b}$	$3V + 2R + D^{b}$	Allocated to all products	Only recyclability considered	Allocated to last product	++	
	Virgin a ratio R_2	R^{b}	R^{b}	$V + D^{b}$	$V + 2R + D^{a}$	Allocated to last product			+	
100:0	No	V^{b}	R^{b}	$R + D^{b}$	$V + 2R + D^{a}$	Allocated to 1st product	Only recycled content considered	Allocated to last product	+++	
100:100	No	$V + R^{a}$	$2R^{a}$	$R + D^{a}$	$V + 4R + D^{b}$	Allocated to 1st product	Allocated to both previous and next product	Allocated to last product	++	
	Virgin a ratio R_2	R^{b}	$2R - V^{b}$	$R + D^{a}$	$4R + D - V^{b}$	No burden, only benefit			+	
	Input mix a ratio R_2	R^{b}	R^{b}	$R + D^{a}$	$3R + D^{b}$	No burden	No consistent allocation		+	
	Virgin a ratio $\min(R_2,\|R_2—R1\|)$	R^{b}	$2R^{a}$	$R + D^{a}$	$4R + D^{b}$	No burden	Allocated to both previous and next product		+	
50:50	No	$V + 0.5R^{b}$	R^{b}	$0.5R + D^{b}$	$V + 2R + D^{a}$	Allocated to 1st product	50% allocated to previous and next product	Allocated to last product	++	
	Virgin a ratio $R_2/2$	$0.5V + 0.5R^{b}$	$R - 0.5V^{b}$	$0.5R + D^{b}$	$2R + D^{b}$	50% allocated to 1st product			+	
BPX 50/50 adapted	Virgin a ratio $R_2/2$	$0.5V + 0.5R + 0.5D^{b}$	R^{b}	$0.5V + 0.5R + 0.5D^{b}$	$V + 2R + D^{a}$	50% allocated to 1st and last product, nothing to product(s) in between	50% allocated to previous and next product	50% allocated to 1st and last product, nothing to product(s) in between	+	E_D assumed to be equal for all products, while it might differ.
Degressive linearly	No	$5/9V + 1/9D + 0.5R^{b}$	$3/9V + 3/9D + R^{b}$	$1/9V + 5/9D + 0.5R^{b}$	$V + 2R + D^{a}$	Allocated to all products degressively	50% allocated to previous and next product	Allocated to all products degressively	−	Considers the number of times a product is recycled (n).

$V = E_V$, $R = E_{recycled} = E_{recycling,EoL}$ and $D = E_D$

[a] Not ok

[b] Ok

degressive linearly because these allocate part of the disposal impact to previous products in the overall system;

- The formula with the highest level of practicality (+++) is the "100:0_no credit" formula because it does not require to estimate the impact due to recycling at EoL nor the change in inherent properties. There are three approaches which score a little lower on the practicality criterion (++) because they do require to estimate the impact due to the recycling at EoL, i.e. the "0:100_no credit", "100:100_no credit" and the "50:50_no credit" approaches. These however do not require knowing the avoided virgin production due to recycling at EoL. The latter is however required by the remaining formulas and these are therefore identified to have an even lower practicality level (+). The degressive linearly method scores the worst on this criterion because it requires to know the number of times a product is being recycled. This number is however unknown and difficult to predict. Although proposals are made to estimate this parameter (Yamada et al. 2006), to date, the uncertainty of this parameter is to be seen as high for many products;
- Changes in inherent material properties are taken into account by all approaches except for the approaches without crediting. For the majority of the methods, the changes in inherent material properties is captured by considering changes in material qualities (Q_S/Q_P), except for the degressive linearly method which considers this implicitly in the number of times (n) a product or material is being recycled;
- Final remarks:

– The BPX 50/50_adapted approach distributes the disposal impact over the different products. It does however not make a difference in the impact due to disposal of the different products in the overall system. As long as the disposal impacts are the same for the different products in the chain, this differentiation is not important. However, when the impact due to disposal is different for the different products in the overall system, a differentiation is needed to ensure physical realism at the overall system level.
– This can be illustrated based on the example in Fig. 1. The BPX 50/50_adapted approach results in the following environmental impact for the three products (assuming there is no quality difference between the three products):

$$EF_A = V_A + 0.2 \times R_{AB} - 0.2 \times V_B + 0.8 \times D_A$$

$$EF_B = 0.8 \times V_B + 0.2 \times R_{AB} + 0.4 \times R_{BC} - 0.4 \times V_C + 0.4 \times D_B$$

$$EF_C = 0.6 \times V_C + 0.4 \times R_{BC} - 0.4 \times V_C + 0.6 \times D_C$$

$$EF_A + EF_B + EF_C = V_A + 0.6 \times V_B + 0.2 \times V_C + 0.4 \times R_{AB} + 0.8 \times R_{BC} + 0.8 \times D_A + 0.4 \times D_B + 0.6 \times D_C$$

Which does not equal the environmental impact of the overall product cascade system:

$$EF_{A\text{–}B\text{–}C} = V_A + 0.6 \times V_B + 0.2 \times V_C + 0.4 \times R_{AB} + 0.8 \times R_{BC} + 0.6 \times D_A + 0.2 \times D_B + {}^{B}D_C$$

– The degressive linearly approach is the only method considering the number of times (n) a product or material is being recycled. The higher this number, the lower the impact of the products. If, for example, there would be a product B′ added in the overall system analysed in Table 4, n would increase from three to four products and the impact of product A would reduce to $7/16V + 1/16D + 0.5R$, the impact of product B = B′ would reduce to $4/16V + 4/16D + R$ and the impact of product C to $1/16\ V + 7/16D + 0.5R$. The mass balance of the overall system remains correct.
– The degressive linearly consists of two formulas while the aim of the EF is to have a single formula to ensure consistency. If this approach would be chosen for the EC EF, the two formulas would need to be transformed in a single formula.

From the eleven analysed formulas in this first step of analysis, six formulas were selected for a quantitative analysis in a second analytical step. These are the formulas leading to physical realistic results at the overall system level (i.e. formulas 1b, 2, 4a, 5 and 6) and hence complying the 100% rule required by the ISO standards, and the 100:100_no credits approach (formula 3a) which results in correct physical results for the three products within the overall product system.

3.2 Results of the second step of the analysis

In the second analytical step, the contribution of the virgin production, the recycling process of the recycled content, the recycling process at EoL, the disposal and the credits related to recycling to the overall environmental impact were analysed. The analysis was made for the six products of Table 2 and for the different R_1/R_2 scenarios of Table 3. The different scenarios of these different cases were analysed with the six shortlisted formulas.

3.2.1 Analysis of the six shortlisted formulas for several product scenarios

At first, the results for aluminium for *the first four R_1/R_2scenarios* (i.e. these correspond to the products A, B and C from the previous analytical step and virgin production with disposal at EoL) are discussed. The overall environmental impact of 1 kg virgin aluminium which is disposed at its EoL equals 9.7 kg CO_2 equivalents. The results for the other three scenarios are presented in Fig. 4, 5 and 6. The analysis of product A (recycled at EoL instead of disposal) in case of aluminium (Fig. 4) illustrates that recycling at EoL is only beneficial compared with disposal according to the formulas "0:100_credit virgin a ratio of R_2", BPX 50/50_adapted and degressive linearly. For the first two formulas, this is because avoided virgin production when recycling at EoL is considered. In case of the degressive linearly approach, this is because the virgin production is distributed over all products (*n* equals 3). The 100:0_no credits formula does not lead to any difference in result (because recycling at EoL is not considered (0 impact) and also disposal does not lead to any climate change impact), while the remaining two formulas (i.e. 100:100_no credits and 50:50_no credits) lead to an increase due to the higher impact of the recycling process than the disposal and due to the fact that avoided virgin production is not accounted for.

The analysis of product B (i.e. consisting of recycled content an being recycled at EoL) in case of aluminium (Fig. 5) illustrates that the highest impact is assigned by the degressive linearly approach. All other methods result in an overall environmental impact which equals the impact of the recycling process or half of it.

The analysis of product C (i.e. consisting of recycled content and being disposed at EoL) in case of aluminium (Fig. 6) illustrates that recycled content does not lead to any reduction in the product's overall environmental impact compared with virgin production according to the 0:100_credit virgin a ratio of R_2 formula. As the EC EF methods aim at including both recycled content and recyclability, the "0:100_credit virgin a ration of R_2" formula was found inappropriate. The BPX 50/50_adapted and linearly degressive formulas assign part of the virgin production to product C (consisting of 100% recycled content) and therefore result in a lower life cycle environmental impact compared with 100% virgin production. The BPX 50/50 formula allocates this virgin production of the recycled content to a greater extent to product C than the degressive linearly formula because it uses the 50:50 approach for the allocation of the virgin production, while the degressive linearly approach allocates the virgin production over the three products A, B and C with the lowest share to product C. All other formulas assign only the impact due to recycling, or half of it, plus the impact of the disposal process (which is 0 in case of aluminium) to product C.

The comparison of the analysis of product A and B reveals that the first formula "0:100_credit virgin a ratio R_2" does not make any difference between the two products, or hence does not differentiate between virgin products or recycled products, even if both have a different impact. As the aim of the EC EF method is to consider recycled content, this formula was excluded as an option for the EC EF method. The comparison of the analysis of product A and C in case of aluminium moreover clarifies that recycled content (product C) leads to a lower overall environmental impact than recyclability (product A) for four of the six formulas, i.e. 100:0_no credits, 100:100_no credits, 50:50_no credits and the degressive linearly formulas. The opposite is true for the 0:100_credit virgin a ratio of R_2 formula and no difference is noticed for the BPX 50/50_adapted formula. This can be an important issue when choosing between the methods: as recyclability at EoL is more difficult to predict (especially for some long-lasting products) and therefore has a higher level of uncertainty, it may be justified to choose for an EoL approach which assigns an equal or higher impact to EoL recycling than to recycled content. For the EC EF methods this was however not a decisive criterion.

An extension of the analysis of aluminium to *all* R_1/R_2*scenarios* (Table 3) is presented in Fig. 7. The first four column-bars of each method summarise the results of the three previous figures and confirm the earlier findings. The last three column-bars of each method represent new scenarios

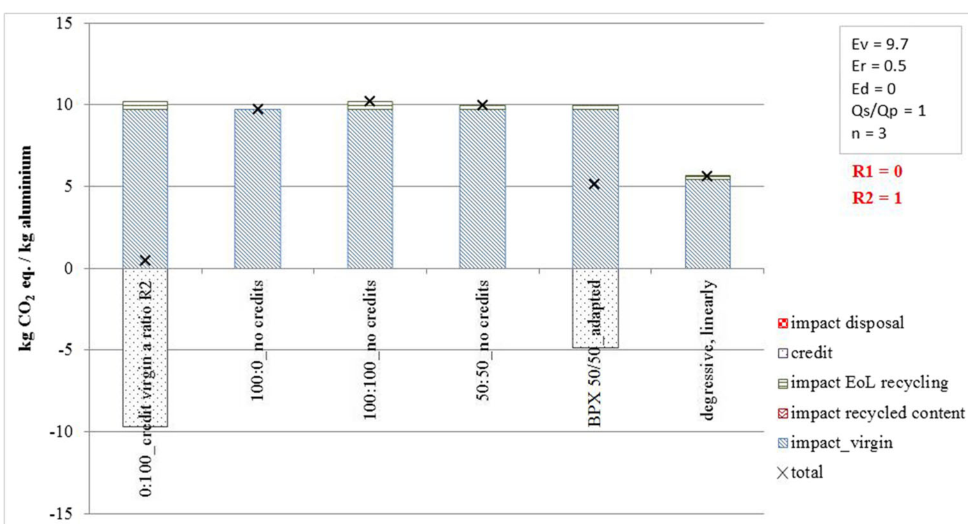
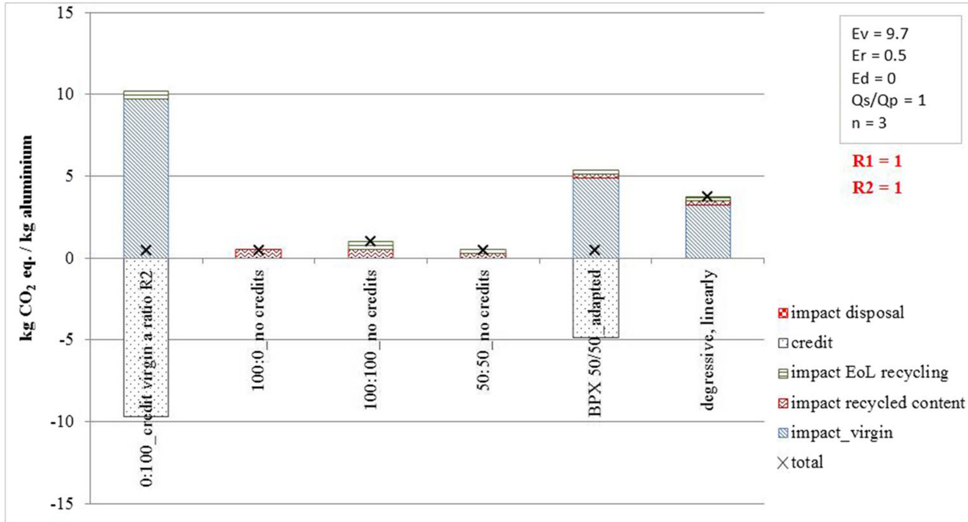


Fig. 4 Comparison of the assessment of product A ($R_1 = 0\%$ and $R_2 = 100\%$) with the six shortlisted (step 1) formulas analysed for aluminium

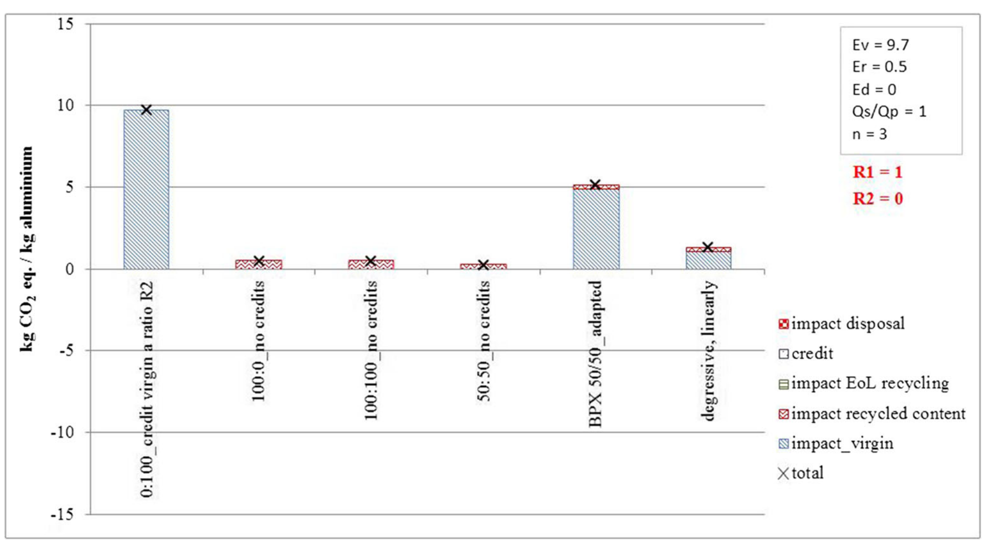
Fig. 5 Comparison of the assessment of product B ($R_1 = 100\%$ and $R_2 = 100\%$) with the six shortlisted (step 1) formulas analysed for aluminium



regarding R_1 and R_2 for the case of aluminium (i.e. $R_1 = 80\%$ and $R_2 = 30\%$; $R_1 = 30\%$ and $R_2 = 80\%$; $R_1 = 30\%$ and $R_2 = 95\%$). These additional analyses reveal that the recyclability rate does not make any difference when using the 100:0_no credits formula for aluminium (i.e. the impact of the last two options (i.e. last two column-bars) are identical). The reason is that this formula only accounts for recyclability as a reduction in the disposal impact. The disposal impact is however zero for aluminium. As the disposal impact is not zero for all materials the 100:0_no credits formula can result in different overall impacts for differing recyclability ratios. This is confirmed in the analysis of paper (see Electronic supplementary material, Fig. S1). The impact of disposal is for many products negligible compared with the impact of production. The 100:0_no credits formula and any other EoL formula which account for "recycling at EoL" solely by avoided landfill, hence hardly reflect major benefits of recycling (i.e. avoided virgin production). It moreover does not consider the impact of the recycling process at EoL, although this is physical reality. For these reasons, it was decided that for the EC EF methods, the 100:0_no credits formula was inappropriate. This formula does not reflect the difference in life cycle environmental impact when the product is being recycled at EoL compared with disposal, and this for an important group of products on the market (i.e. the products with a negligible disposal impact). But, more importantly, it does not consider the impact of the recycling process, which is physically occurring.

The analysis of aluminium (Fig. 7) furthermore reveals that two of the six formulas (i.e. 100:100_no credits and 50:50_no credits) lead to a higher life cycle impact when aluminium is recycled at EoL than when it is disposed of (third compared with first column-bars). This is due to the fact that for aluminium the recycling impact is higher than the disposal impact and the reduced virgin production is not accounted for. For PVC, similar results were obtained. For the case of paper

Fig. 6 Comparison of the assessment of product C ($R_1 = 100\%$ and $R_2 = 0\%$) with the six shortlisted (step 1) formulas analysed for aluminium



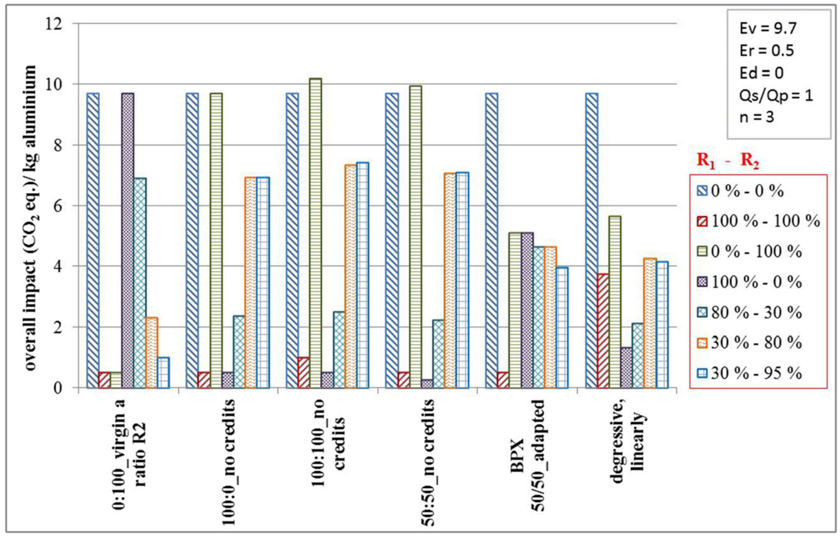


Fig. 7 Assessment result of aluminium for different R1/R2 scenarios, calculated with the shortlisted (step 1) formulas

(Electronic supplementary material, Fig. S1), results are different, i.e. recycling at EoL results in a lower impact than disposal for the abovementioned formulas, because the disposal impact is higher than the recycling impact. As for most products, the disposal impact is lower than the recycling impact, the results obtained for aluminium (and PVC) are more likely to occur. For the EC EF methods it was decided that the 100:100_no credits and the 50:50_no credits are not appropriate because the physical reality of reduced virgin production due to recycling at EoL is not considered.

3.2.2 Analysis of double counting at the overall product cascade system level

The double counting at the product cascade system level identified in the first analytical step for the 100:100_no credits approach was confirmed in the second analytical step and illustrated in Fig.8 for extreme case 2 (high recycling impact, i.e. half of impact due to virgin production). Figure 8 illustrates that according to formula 100:100_no credits an overall system consisting of three identical virgin products, each of them disposed at their EoL leads to a lower life cycle impact than a system consisting of three products out of one virgin production. As the impact due to recycling of this extreme case 2 is only about half of the impact due to virgin production (i.e. 5 compared with 9.7, see Table 2), these results are only possible due to double counting at the overall system level. It was hence decided that the 100:100_no credits is not appropriate for the EC EF methods.

3.2.3 The importance of considering the number of recycling cycles (n)

Based on the previous analyses, two formulas, i.e. BPX 50/50_adapted and degressive linearly, were found

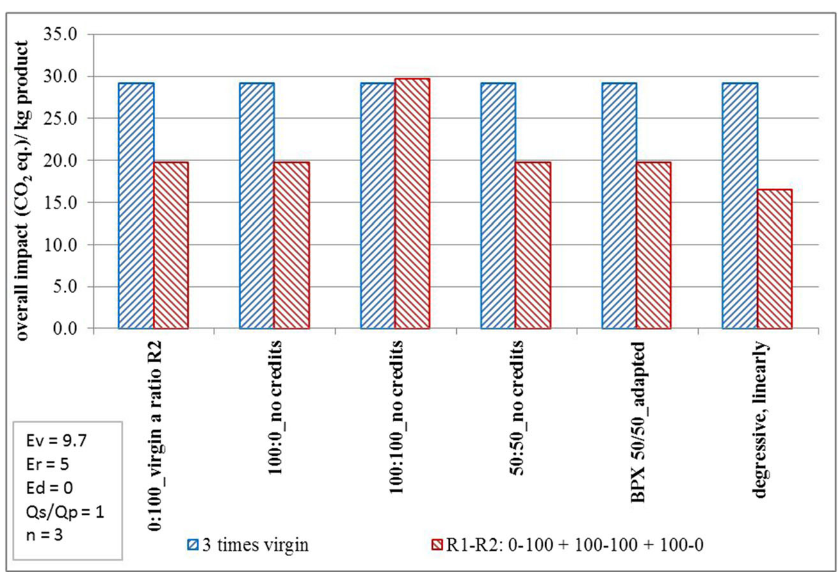


Fig. 8 Assessment result of extreme case 2 comparing a system consisting of three virgin products disposed at EoL with a system consisting of “virgin-recycled-recycled-disposed”, calculated with the six shortlisted formulas

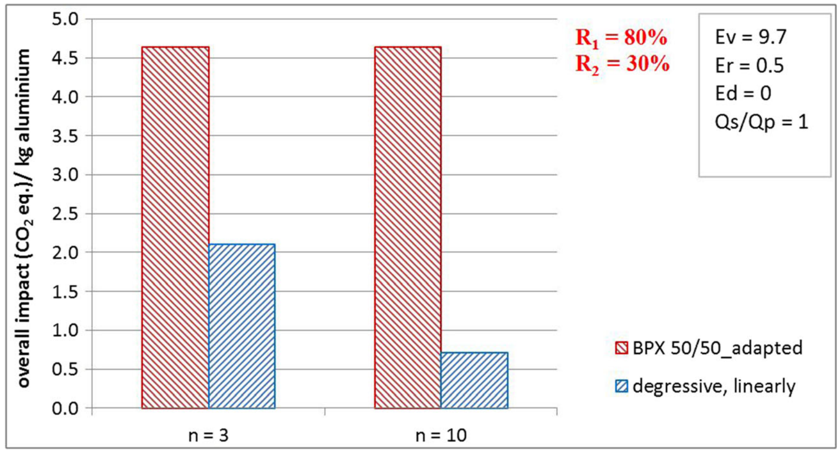


Fig. 9 Assessment result of aluminium in case the number of recycling cycles (n) equals 3 compared with 10, according to the "BPX 50:50_adapated" and "linearly degressive" formulas

appropriate for the purpose of the EC EF methods. An important difference between these two formulas is the number of times (n) a material/product is being recycled. This is only taken into account in the degressive linearly approach as illustrated in Fig. 9. For the aluminium case, the scenario where three products are produced out of a single virgin production is compared with the scenario where ten products are produced out of the same virgin production. According to the BPX 50/50_adapted approach, there is no difference in impact for both scenarios, while the degressive linearly approach assigns a smaller impact to the product with a higher number of recycling cycles. In the extreme scenario where n goes to "endless", the impact would equal the recycling impact and no impact would be allocated for virgin production and disposal.

3.2.4 Selected EoL formula for the EC EF method

Although the degressive linearly formula is preferred from the viewpoint of physical realism and as it distributes burdens and benefits over all products related to material that is repeatedly recycled in a product cascade system, this formula fails the third criterion practicality. As to date, not enough information is available on the number of times a product/material can/will be recycled this approach was found inappropriate for the EC EF methods (which needs to be applicable for all products on the market). The BPX 50/50_adapted formula was therefore selected as the preferred formula out of the 11 formulas analysed for the purpose of the EC EF methods.

One additional adaptation to the original formula was however made. As highlighted in Sect. 3, it was found that the BPX 50/50_adapted formula as used in the analysis described in this paper does not allow differentiating the disposal impacts of the different products in the overall product cascade system. The last part of the BPX 50/50_adapted formula has therefore been slightly changed, resulting in the following EoL formula for the EC EF methods (incineration with energy recovery excluded here):

$$\mathrm{EF} = \left(1-\frac{R_1}{2}\right) \times E_\mathrm{V} + \frac{R_1}{2} \times E_\mathrm{recycled} + \frac{R_2}{2} \times \left(E_\mathrm{recycling,EoL} - E^*_\mathrm{V} \times \frac{Q_\mathrm{S}}{Q_\mathrm{P}}\right) + \left(1-\frac{R_2}{2}\right) E_\mathrm{D} - \frac{R_1}{2} \times E^*_\mathrm{D}$$

with all terms as defined before and E^*_D = specific emissions and resources consumed (per unit of analysis) arising from disposal of waste material at the EoL of the material where the recycled content is taken from.

Finally, we want to remark that based on the physical realism criterion, it would be preferred to give credits to avoided production of the market mix instead of to virgin production for recycling at EoL. The practicality criterion contradicts this because this is not known for all materials on the market. The proposal to credit 50% virgin and 50% recycled material, as proposed by Ekvall (2000) is not followed neither because this would either assume that the same recycling process is replaced (which is not always the case) or require the recycling processes (from other products) to be known. The latter fails our criterion of practicality. The avoided disposal impact (E^*_D) due to the recycled content is also a simplification of reality as in a saturated market with a lack of secondary raw materials the avoided impact of the recycled content is most likely not disposal, but another recycling process. As this avoided recycling process is often unknown, it is decided because of the criterion practicality to restrict this to avoided disposal impact.

4 Conclusions

There exists no purely natural-science-based approach to separate the different products in an overall system where recycling occurs. To avoid the current situation of diverging methods and approaches and to achieve a higher degree of comparability of results, in the context of the EC Environmental Footprint, more specific conventions had to be identified. More specifically, prescriptive rules regarding system boundaries and necessary allocation were needed in line with the goal and scope of EC Environmental Footprint method. Clear and transparent reporting of the conventions is seen as crucial in order to allow correct interpretation and enhance acceptability. In this context, this paper focuses on the EoL approach selected for the purpose of the EC Environmental Footprint method by explaining in details how the approach builds on existing EoL approaches, and how and why the selected approach also deviates from them.

The objectives of the EoL approach in the EC Environmental Footprint method are summarised as supporting comparability at product level (i.e. to allow for labelling products), being comprehensive by including both recycled content and recyclability, enhancing acceptance, being applicable for any product on the market and being physically correct. As the EC Environmental Footprint method aims at providing a common base for measuring and communicating environmental performance of products and organisations, an agreed basis as a starting point was important (i.e. objective of acceptance). EoL approaches from existing standards/guidelines were hence considered as a starting point. In terms of consistency and to allow for comparability of environmental footprint of products, it was preferred to have a single EoL formula for the purpose of the EC Environmental Footprint method. Eleven EoL formulas allowing for assessment at the product level (i.e. objective of comparability at product level) were identified and analysed based on three criteria, reflecting the remaining objectives of the EC Environmental Footprint method: physical realism, distribution in a cascade system and practicality.

Based on a two-step analytical process, two EoL approaches were withheld. The first approach, degressive linearly, considers the number of times a material is being recycled and was found appropriate based on the criteria of physical realism and distribution in a cascade system, but failed the criterion of practicality. The second approach—chosen for the EC Environmental Footprint methods—is a slightly adapted version of the BPX 50/50 approach and was found appropriate based on all three criteria, although its shortcoming by not considering the number of recycling cycles and the practicality issues related to the assessment of the reduced virgin resources (in the subsequent product) due to recycling at EoL were recognised. This approach distributes the environmental impact of the virgin production, recycling processes and disposal amongst the different products of the cascade system. The EoL formula in the EC EF methods is based on the BPX 50/50 approach but differentiates recycled content and recyclability at EoL, considers the quality reduction of the secondary material compared with the primary material and takes into account different disposal impacts of the products in the cascade system. In the ongoing ~25 pilots[2] that are developing Product Environmental Footprint Category Rules and Organisation Environmental Sector Rules, this EoL approach is taken as the baseline approach. The paper will surely be valuable to the pilots to explain better the background and motivations for the EOL allocation formula in the PEF/OEF method and the overall aim strived for. It should also be useful by demonstrating the workability of the formula thanks to the quantitative analysis. The EF pilots are encouraged to test other approaches (amongst others the degressive linearly approach) and to document and interpret any diverging outcomes and learnings. This will inform the decision after the end of the pilots whether to keep the EoL formula unchanged or to adapt the approach according to those "real-world learnings".

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References

AFNOR (2011) Repository of good practices. General principles for an environmental communication on mass market products. Part 0: general principles and methodological framework (BP X30-323-0). Paris, France

Allacker K, Mathieux F, Manfredi S, Pelletier N, De Camillis C, Ardente F, Pant R (2014) Allocation solutions for secondary material production and end of life recovery: proposals for product policy initiatives. Resour Conserv Recyl 88:1–12

Boguski TK, Hunt RG, Franklin WE (1994) General mathematical models for LCI recycling. Resour Conserv Recycl 12(3–4):147–163

Borg M, Paulsen J, Trinius W (2001) Proposal of a method for allocation in building-related environmental LCA based on economic parameters. Int J Life Cycle Assess 6(4):219–230

BSI (2011) PAS 2050:2011. Specification for the assessment of the life cycle greenhouse gas emissions of goods and services. British Standards Institution, London

[2] More information on the EF pilots can be found at http://ec.europa.eu/environment/eussd/smgp/index.htm

Buhé C, Achard G, Le Téno JF, Chevalier JL (1997) Integration of the recycling processes to the life cycle analysis of construction products. Resour Conserv Recycl 20(4):227–243

Byström S, Lönnstedt L (2000) Paper recycling: a discussion of methodological approaches. Resour Conserv Recycl 28:55–65

CEN (2011) EN 15978 Sustainability assessment of construction works—assessment of environmental performance of buildings—calculation method

CEN (2013) EN 15804:2012+A1 Sustainability of construction works—Environmental product declaration—core rules for the product category of construction products

Council of the European Union (Council) (2010) Council conclusions on sustainable materials management and sustainable production and consumption: key contribution to a resource-efficient Europe. www.consilium.europa.eu/uedocs/cms_data/docs/pressdata/en/envir/118642.pdf. Accessed 17 July 2014

Ekvall T (2000) A market-based approach to allocation at open-loop recycling. Resour Conserv Recycl 29:91–109

Ekvall T, Tillman AM (1997) Open-loop recycling: criteria for allocation procedures. Int J Life Cycle Assess 2(3):155–162

European Aluminium Association (EAA) (2008) Environmental Profile Report for the European Aluminium Industry—Life Cycle Inventory data for aluminium production and transformation processes in Europe

European Commission (EC) (2003) COM(2003) 302 final: communication from the commission to the council and the European Parliament. Integrated Product Policy—Building on Environmental Life-Cycle Thinking. http://eur-lex.europa.eu/LexUriServ/LexUriServ.do?uri=CELEX:52003DC0302:EN:NOT. Accessed 12 August 2013

European Commission (EC) (2011) COM(2011) 571 Final: Roadmap to a Resource Efficient Europe. Communication from the Commission to the European Parliament, The Council, The European Economic and Social Committee and The Committee of the Regions

European Commission (EC) (2013a) COM(2013) 196 Final: Communication from the Commission to the European Parliament and The Council: "Building the Single Market for Green Products—facilitating better information on the environmental performance of products and organisations". Brussels

European Commission (EC) (2013b) Annex II: Product Environmental Footprint (PEF) Guide to the Commission Recommendation (2013/179/EU) on the use of common methods to measure and communicate the life cycle environmental performance of products and organisations

European Commission (EC)-Joint Research Centre (JRC)-Institute for Environment and Sustainability (IES) (2010) International Reference Life Cycle Data System (ILCD) Handbook—general guide for life cycle assessment—detailed guidance. First edition March 2010. Luxembourg. Publication Office of the European Union. http://lct.jrc.ec.europa.eu/assessment/. Accessed 24 May 2013

Fava JA, Denison R, Jones B, Curran MA, Vigon B, Selke S, Barnum J (eds) (1991) A technical framework for life cycle assessments, SETAC-workshop during 18–23 August, 1990, Smugglers Notch. Vermont, Washington, DC

Finkbeiner M (2014) Product environmental footprint—breakthrough or breakdown for policy implementation of life cycle assessment. Int J Life Cycle Assess 19:266–271

Frischknecht R (2000) Allocation in life cycle inventory analysis for joint production. Int J Life Cycle Assess 5(2):85–95

Frischknecht R (2010) LCI modelling approaches applied on recycling of materials in view of environmental sustainability, risk perception and eco-efficiency. Int J Life Cycle Assess 15:666–671

Galatola M, Pant R (2014) Reply to the editorial "product environmental footprint—breakthrough or breakdown for policy implementation of life cycle assessment?" written by Prof. Finkbeiner (Int J Life Cycle Assess 19(2):266–271). Int J Life Cycle Assess 19:1356–1360

ISO (2006a) ISO 14040:2006—environmental management—life cycle assessment—principles and framework. International Standard Organisation, Geneva, Switzerland

ISO (2006b) ISO 14044:2006—environmental management—life cycle assessment—requirements and guidelines. 2006. International Standard Organisation, Geneva

ISO (2012) ISO/DIS 14067—carbon footprint of products—requirements and guidelines for quantification and communication (draft). International Standard Organisation, Geneva

Jensen AA, Hoffman L, Moller BT, Schmidt A (1997) Environmental issues series no. 6—life cycle assessment (LCA)—a guide to approaches, experiences and information sources. European Environment Agency, Copenhagen

Kim S, Hwang T, Lee KM (1997) Allocation for cascade recycling system. Int J Life Cycle Assess 2(4):217–222

Klöpffer W (1996) Allocation rule for open-loop recycling in life cycle assessment—a review. Int J Life Cycle Assess 1(1):27–31

Lindfors LG, Christiansen K, Hoffman L, Virtanen Y, Juntilla V, Hanssen OJ, Ronning A, Ekvall T, Finnveden G (1995) Nordic guidelines on life cycle assessment. Nord 1995:20, Nordic Council of Ministers, Copenhagen

Nicholson AL, Olivetti EA, Gregory JR, Field FR, Kirchain RE (2009) End-of-life allocation methods: open loop recycling impacts on robustness of material selection decisions. Proceedings of the International Symposium on Sustainable Systems and Technology, 18–20 2009, pp. 1–6. doi: 10.1109/ISSST.2009.5156769

Pears A, Grant T (2005) Allocation issues in life cycle assessment—benefits of recycling and the role of environmental rating schemes. Proceedings of the 4th Australian Conference on LCA, Sydney, Australia

Pré Consultants (2012) Simapro Software www.pre-sustainability.com/download-software. Accessed December 2012

SCA (2014) Evaluation of recycling and allocation methods for paper—The Swedish Life Cycle Center report no. 2014:1, Göteborg

Swiss Centre for Life Cycle Inventories (2013) Ecoinvent v2.2. www.ecoinvent.ch/. Accessed December 2012

Villanueva A, Wenzel H (2007) Paper waste—recycling, incineration or landfilling? A review of existing life cycle assessments. Waste Manag 27:S29–S46

Vogtländer JG, Brezet HC, Hendriks CF (2001) Allocation in recycling systems—an integrated model for the analyses of environmental impact and market value. Int J Life Cycle Assess 6:1–11

Wardenaar T, Ruijven van T, Beltran AM, Vad K, Guinée J, Heijungs R (2012) Differences between LCA for analysis and LCA for policy: a case study on the consequences of allocation choices in bio-energy policies. Int J Life Cycle Assess 17:1059–1067

Werner F, Richter K (2000) Economic allocation in LCA: a case study about aluminium window frames. Int J LCA 5(2):79–83

World Resources Institute (WRI), World Business Council for Sustainable Development (WBCSD) (2011) Product life cycle accounting and reporting standard. Greenhouse Gas Protocol. WRI & WBCSD, US

Yamada H, Daigo I, Matsuno Y, Adachi Y, Kondo Y (2006) Application of Markov chain model to calculate the average number of times of use of a material in society. Int J Life Cycle Assess 11(5):354–360